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Integrating proprioceptive assessment with proprioceptive training of stroke patients

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Abstract— **Although proprioceptive impairment is likely to affect in a significant manner the capacity of stroke patients to recover functionality of the upper limb, clinical assessment methods in current use are rather crude, with a low level of reliability and a limited capacity to discriminate the relevant features of the deficits. In this paper we describe a new technique based on robot technology, with the goal of providing a reliable, accurate, quantitative evaluation of the position sense in peri-personal space. The proposed technique uses a bimanual, planar robot manipuladum (BdF device), whose handles are grasped by the blindfolded patient: the paretic hand is passively placed in one of 17 positions and the subject is asked to actively match the paretic hand position in space with the other hand. The position sense of the paretic arm and the corresponding deficit of space representation are characterized by means of 7 indicators: 1) positional error; 2) holding force; 3) medio/lateral shift; 4) antero/posterior shift; 5) medio/lateral skew; 6) antero/posterior skew; 7) shrink coefficient. We also show how the same experimental setup can be used for "proprioceptive training", i.e. for providing robot assistance to the paretic arm that may improve the position sense of the patient. A preliminary, feasibility test has been carried out with one patient and three controls.**

Keywords: bimanual robot, position sense, proprioceptive training.

I. Introduction

Multisensory integration of the information from muscle spindles, Golgi tendon organs, joint and cutaneous receptors of the arms allows the human brain to be aware of the relative position of the two hands as well as their positions in the peri-personal space, in the absence of visual feedback. This integration capacity is crucial for conceiving and carrying out purposive actions in everyday life but is frequently impaired in stroke patients [1] and this is a strong obstacle for the recovery of sensorimotor functions. Clinical observations suggest that intact position sense following stroke strongly correlates with motor recovery of the paretic arm and is predictive of long-term motor recovery [2-4]; however, clinical tools used so far for evaluating position sense are rather crude [5] because have very poor reliability and sensitivity; moreover, even when more quantitative measures are used they address single joints, thus missing the integrative nature of the limb position sense.

A notable exception is the recent paper by Dukelow et al. [6] who used the KINARM device [7], by fitting each arm of the subjects in one of two exoskeletons: one arm was passively placed in one of 9 positions, in one half of the workspace, and the subject was told to actively mirror-match the other arm in the contralateral hemi space. This procedure provides a quantitative assessment of the limb position sense but the comparison is performed in the joint configuration space and is limited by the fact that only one-half of the space can be tested in order to avoid interference between the two exoskeletons.

In this paper we propose an alternative method, based on a bimanual manipulandum [8] rather than a bimanual exoskeleton [7]. The bimanual interference problem is avoided by slightly shifting the plane of action of the two manipulanda and the subject is asked to actively match the hand position of the paretic arm with the healthy arm, using a set of 17 test points, balanced in the two halves of the workspace. In other words, matching is performed in the extrinsic peri-personal space, instead of the intrinsic joint space and this means that what is assessed is the *hand position sense* rather than the *limb position sense.* Although the two types of sensory information are related, we think that the former one requires a higher level of multisensory integration than the latter and thus the assessment is more informative from the functional point of view: in tasks of everyday life the hand position sense is the crucial element for skilled bimanual behavior, not the limb position sense.

Since *proprioceptive assessment* should always be integrated with *proprioceptive training*, in order to provide adaptive assistance, we also tested a robot treatment mechanism that uses the same experimental setup, i.e. the bimanual manipulandum mentioned above. The motivation comes from previous studies on the use of robot assistance, provided by a single manipulandum, for the functional recovery of the upper limb mobility of stroke survivors: we proposed the concept of *proprioceptive training* and we applied it to discrete reaching [9], continuous tracking movements [10] and bimanual movements [11]. In these cases, the robot controller operated with a very small stiffness, in order to avoid passive mobilization of the paretic limb, and the assistive force was modulated to a minimum value while keeping its orientation to the target, in order to promote the emergence of voluntary control patterns. We alternated trials with open eyes, where the position of both hand and target was visualized on a computer screen, and trials with closed eyes, where hand/target position could only be detected by the subjects by focusing on proprioceptive information, i.e. the perception of the position, motion, and target-oriented force, based on sensory information from muscle spindles, Golgi tendon organs, joint and cutaneous receptors, and efferent copies of motor commands. The results suggested that this interactive mechanism can promote the improvement of motor control indicators and enhance, at the same time, the role of proprioception in learning and control. However, no specific quantitative assessment of proprioceptive awareness could be given by that experimental setup because a suitable bimanual device is necessary to carry out some kind of comparison between the paretic and the non-paretic limb.

The bimanual robotic assistance mechanism proposed here uses the same set of 17 target points, balanced in the peri-personal workspace, with the difference that in this case the non-paretic hand (passively placed by the robot in one of the 17 test points) is the target of the paretic hand and the motion of the arm is robot-assisted by a smooth force field.

Summing up, during *proprioceptive assessment* the position of the paretic hand is the target of the un-assisted healthy arm, whereas during *proprioceptive training* the position of the healthy hand is the target of the robot-assisted paretic arm. When the target is reached, in either modality, the brain of the user is informed that efferent and afferent signals are matched and we believe that this is likely to be a powerful reinforcement mechanism for the recovery of sensorimotor functions. The two interactive modalities of proprioceptive assessment and training were implemented and preliminary tests were carried out with a single, severely impaired patient and three controls.

II. Methods

A. The experimental setup

A bimanual robot system was used in the experiments. It consists of two identical robot manipulanda, each with two degrees of freedom, mounted in a mirrored configuration on the same frame (fig. 1). The system (BdF2, Celin srl, La Spezia, Italy) is a direct evolution of the uni-manual planar robot manipulandum Braccio di Ferro (BdF) [8]. In particular, the two robots are fully back-drivable, with negligible friction and small inertia, thus allowing the direct estimate of the force transmitted by each robot to the grasped handle by means of the current drives to the motors and the Jacobian matrix of the robot. The two robots were positioned horizontally at a distance that approximately matched the distance between the two shoulders (38.5cm). The vertical positions (under motorized control) were separated by about 15cm in order to avoid interference between the two hands. The forearm of the paretic hand, which grasped the handle of the lower robot (**R1**), was supported by a suitable holder that kept it horizontal and its height was adjusted in order to minimize the abduction of the shoulder. For the control subjects the same robot arm (**R1**) was grasped by the non dominant hand. The positions of the two handles were calibrated with respect to a common reference frame, which was also used to specify the target positions. Subjects were seated on a chair, with their torso and wrist restrained by means of suitable holders while grasping the handles of the two manipulanda. A large computer screen, positioned right in front of the subjects, was used to display the current position of both hands and that of the targets, but only for monitoring purpose because the subjects were blindfolded while performing the tasks.

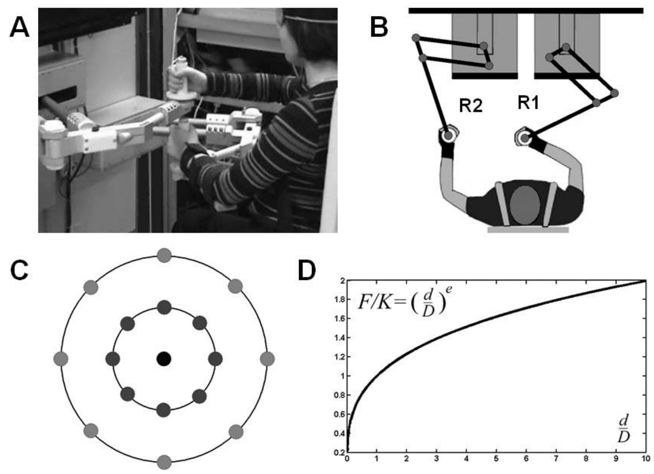

Figure 1. **A & B:** Experimental setup, with the two robots, vertically shifted in order to avoid interference. The lower-robot is grasped by the paretic hand, in the case of the patient, or by the non-dominant hand, in the case of the controls; this robot includes a forearm holder. All the subjects were blindfolded while performing the task. **C**: Layout of the test points or targets: 16 peripheral targets located on two cirles, with 7 and 14cm radiuses, respectively, plus one central target. **D**: Assistive force profile used during proprioceptive training, in which the healthy hand was the target of the paretic arm; the following assistance parameters were used: K=25, D=1.5cm, e=0.3. (d is the distance of the hand from the target.)

B. Subjects

One hemiparetic subject (female, 28 years old) and 3 control subjects (age: 25-33 years) tested the proposed system. The impaired subject was left-hemiparetic, chronic (more than 16 months after a hemorrhagic ictus) with a significant impairment level, at the motor, sensory, functional, and attentive levels, evaluated by means of the following scales or measurements:

- Fugl-Meyer scale, Arm section: 12/66;
- Wolf Motor Function Test: 20/85;
- Modified Ashworth Scale: 2/4;
- Revised Nottingham Sensory Assessment, Arm section: 21/106;
- Grip force (measured by means the hydraulic hand dynamometer of the Baseline Evaluation Instruments Ltd): less than 1N;
- Hemi-inattention (evaluated by means of test no. 4, with control of the fixation point, of the computerized TAP battery of attention tests [12]): the percentage of missed or unattended points (left vs. right) was 58% vs. 31% .

C. Assessment protocol of the hand position sense

Seventeen test-points were used for the assessment (fig. 1.C): a central point (located in the middle of the workspace) and 16 points equally spaced on two concentric circles (radius 7cm and 14cm, respectively). The assessment protocol was articulated in three target-sets, each including 16 trials: a centre-out movement, to a randomly selected peripheral test point, and a return movements to the central position. The subject remained constantly blindfolded during the assessment procedure. Each trial consists of the following steps:

- Starting from the central target $\vec{p}_0$, where both hands were initially positioned, robot **R1** moves passively but smoothly the paretic arm to one of the 16 peripheral targets $\vec{p}_T$ according to a stiff position control and a minimum-jerk imposed profile, with a movement duration *T*=1s ($\xi = t/T$):

$$\vec{p}_{R1}(t) = \vec{p}_0 + (\vec{p}_T - \vec{p}_0)[6\xi^5 - 15\xi^4 + 10\xi^3]$$

  R1 is then kept fixed in test position until the end of the matching operation.
- As soon as **R1** has reached the test position, an acoustic prompt is given, requiring the subject to move the hand grasping **R2** (non-paretic hand for the stroke subject and the dominant arm for the controls) in such a way to match the position of hand **R1**. Robot **R2** is deactivated in this phase and is only used for measuring the hand motion. The end of the matching operation is detected when the speed of **R2** goes below a threshold of 3cm/s. The controller of robot **R2** is then reactivated, with the same stiff and smooth positional control of **R1**, in order to re-align the two robots.
- Starting from the current peripheral target, the same procedure above is carried out for the return movement.

It is worth emphasizing that any recoil movement of the paretic hand is avoided because the stiff positional control of the paretic hand is never switched off during the assessment protocol. Moreover, each trial starts with both hands aligned on the designated starting point.

From the 48 peripheral stopping positions and the 48 centre stopping positions, the displacement/distortion of the space representation is evaluated in graphical terms (by means of a polar plot of the input/output tessellations induced by the test-set) and in quantitative terms by computing the following indicators of the hand position sense:

1) Positional error *PE*, which is the **R1**/**R2** mismatch, at the end of the **R2**→**R1** matching phase.
2) Holding force *HF*, evaluated as the average value of the force necessary to maintain hand **R1** on the current target. *HF* is a measure of the level of hypertonic muscle activity of the paretic hand.
3) Medio/lateral shift Δx and 4) antero/posterior shift Δy of the ensemble average of the matched hand positions with respect to the center of the test area. This index shows the overall shift of the space representation in the medio-lateral and antero-posterior directions.
5) Medio/lateral skew sk_x and 6) antero/posterior skew sk_y of the distribution of matched hand positions. This is a distortion coefficient of the space representation, computed by means of the skewness coefficients defined in statistics (as the third stadardized moment of the distribution). Both coefficients are null for target points, by definition; for the matched stopping points $sk_x>0/sk_x<0$ if they are skewed to the right/left, respectively, and $sk_y>0/sk_y<0$ if they are skewed forward/backward.
7) Shrink coefficient γ, for quantifying the spatial contraction/expansion of the space representation. It describes the range/area of the workspace matched by the active hand (non paretic arm for the stroke patient and dominant arm for the controls) relative to that of the passive hand (paretic arm and non dominant hand for stroke patient and controls, respectively). It is computed from the standard deviations of the matched points and the target points: $\gamma = (\sigma_x\sigma_y)_{R2} / (\sigma_x\sigma_y)_{R1}$.

D. Proprioceptive training protocol

The proposed training procedure uses the same target-set defined above (17 points, 16 centre-out movements and 16 return movements) and is very similar to the assessment procedure, with the difference that the matching direction is reversed (**R1→R2** instead of **R2→R1**) and matching is assisted instead of being free. Each trial is organised as follows:

- Starting from the central target, where both hands are positioned, robot **R2** moves passively the non-paretic hand to one of the sixteen peripheral targets with the same 1s minimum-jerk trajectory used in the assessment protocol.
- At the end of the such positioning a prompt sound is given and the task of the subject is to match the position of the non-paretic hand **R2** with the paretic hand **R1.** With a 1s delay after the sound, the paretic arm's movement is aided by an assistive force (AF) that links the paretic hand **R1** to a moving target **TG**, which reaches the **R2** target with a 3s minimum-jerk profile, delivering the following force:

$$F_{R1\to TG} = K(d/D)^e$$

  (fig. 1.D), where *d* is the current distance between the robot and the moving target **TG**, *D*=1.5cm is a scale factor related to the target size, and *e* = 0.3 controls the curvature of the length-tension curve of the assistive force. The less-than-linear length-tension profile (*e*<1) was chosen in order to have a trade-off between low stiffness assistance, when the error is great, and high stiffness in the vicinity of the target. This condition is quite useful for stabilising the hand position between the end of a trial and the initiation of the next one. The *K* gain sets the level of assistance and it can be adapted, target-set by target-set, according to the evolution of the subject's performance. For the reported experiment *K* was set at 25N/m and remained constant. If the subject cannot reach the target within the nominal time (3s, distance threshold 1.5cm) the controller waits for an additional period of 5.5s, while keeping the same assistance pattern. At the end of such overall time of 1+3+5.5=9.5s, the end-effector position is evaluated (stopping point) and if the target is still unreached (distance threshold > 1.5cm), a restoring force is activated, passively bringing the paretic hand to match the **R2**-hand position. At that point, the paretic hand is maintained for

1s in the target position by a holding force. In this manner recoil movements are avoided and the starting point of each assisted reaching movement is well established.

- Starting from the current peripheral target, the same procedure above is carried out with respect to the central target for the return movement.

The performance of the trained movements is quantified by means of the following parameters:

1) Time-to-target (*TT*) of the smoothly assisted movement;
2) Matching positional error (*PE*), at movement termination;
3) Magnitude of the assistive force (*AF*) at stopping points;
4) Magnitude of the restoring force (*RF)*;
5) Holding force (*HF*) to maintain the paretic arm on the target.

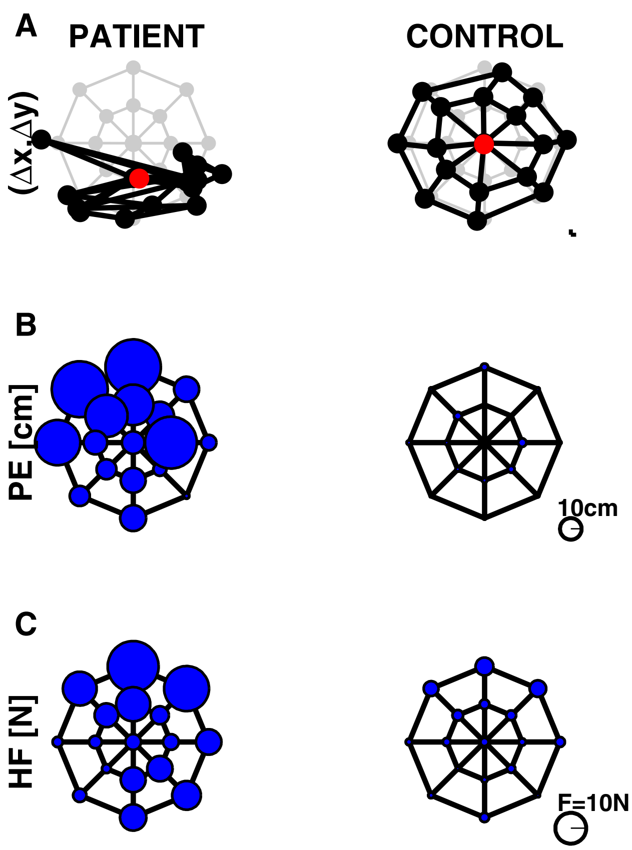

Figure 2. Assessment of the hand position sense. **A**: Polar lattice of the test-points (gray dots) and of the matched points (black dots), with the corresponding barycenter (red dot); Δx, Δy refer to the shift of the barycenter of the lattice with respect to the nominal center. **B**. Average positional errors (PE) over the lattice of test-points, represented by means of circles with a radius proportional to the error. **C**. Average magnitude of the holding force (HF) over the lattice of test-points, represented by means of circles with a radius proportional to the force. "PATIENT" corresponds to the single tested subject; "CONTROL" corresponds to one of the healthy subjects. (Inter-subject variability is rather small, for the controls, compared with the patient.)

III. RESULTS

Let us first consider the assessment procedure of the hand position sense, for the patient and control subjects. Figure 2 shows the relevant graphs. The graphs on the left part refer to the patient and the graphs on the right part refer to one of the controls.

Figure 2.A shows, in the background (light gray), the test-points, arranged as a polar lattice, where robot **R1** keeps the tested hand (paretic hand for the patient and non-dominant hand for the controls) as targets for the other hand. On top of this graph there is the lattice of matched positions, i.e. the positions achieved by robot **R2** at the end of the matching movement. The two polar lattices are well matched in the control subject, as expected, which means that his position sense is accurate and the corresponding representation of the peri-personal space is isotropic. On the contrary, the space representation of the patient is strongly shrinked, with a strong deficit in the forward direction.

The middle pair of graphs (fig. 2.B) show complementary metric information: the average positional error for each test point. In the control subject the error is quite small and rather uniform, suggesting that his space representation is well matched to the proprioceptive stimuli, both in topological and metric terms. In the patient the most deficient part is the left-forward part, where *PE* is much greater than in the other areas of the workspace.

The bottom pair of graphs (fig 2.C) shows the distribution of holding forces over the lattice of test-points, i.e. the forces that the position controller must exert in order to keep the tested hand (the paretic hand for the patient, and the non dominant hand for the control) in the target position. As expected, in the control subject this force is very small, since it is determined by residual, unaccounted constraints induced by the test system as well as some background "motor noise". Therefore, this figure confirms that the experimental setup is sufficiently "ergonomic". The patient, on the contrary, displays a much larger holding force, particularly in the more distant positions.

TABLE I. INDICATORS OF THE HAND POSITION SENSE

	Parameters	*Patient*	*Controls*
1	Positional error, *PE* [cm]	10.34±5.56	2.67±0.97
2	Holding force, *HF* [N]	6.61±3.41	3.13±0.23
3	Medio/lateral shift, Δx [cm]	1.11±8.70	0.99±1.70
4	Antero/posterior shift, Δy [cm]	-6.57±5.12	-0.1±0.84
5	Medio/lateral skew, sk_x	-0.18	-0.05±0.19
6	Antero/posterior skew , sk_y	0.37	-0.19±0.09
7	Shrink coefficient, γ	0.89	1.13±0.06

All together, the graphs of fig. 2 show in qualitative terms the massive impairment of the space representation of the patient, induced by the defective hand position sense, in topologic and metric terms, in comparison with the control subject. A more quantitative picture of the deficit of the hand position sense is provided by the 7 indicators of table I. The "Controls" column, which stores average values of the indicators for the 3 control subjects, provides reference values for evaluating the degree of the deficit in a given patient. In particular, it appears that the positional error of the patient is more than three times the normal value; the holding force is about twice; the space representation is slightly shifted to the right, but strongly shifted backward; moreover, it is strongly skewed and less strongly shrinked.

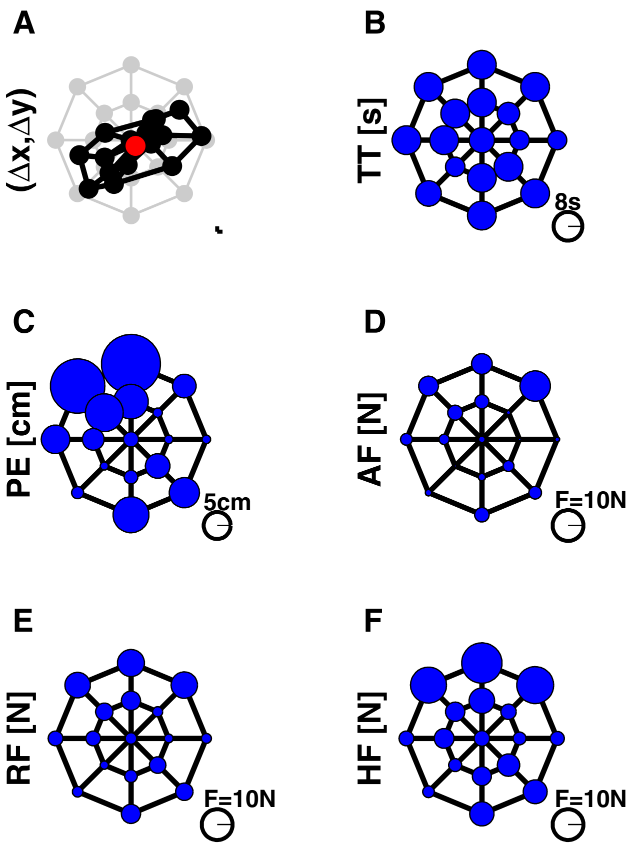

Figure 3. Preliminary evaluation of proprioceptive assistance. Values are computed as the average values over the five target-sets of the treatment phase. **A**. Average of paretic hand positions at the end of the assistance phase (3+5s). The grey lattice represents the target lattice. The red point represents the barycenter of the positions assumed at the end of the assistance phase; Δx, Δy refer to the shift of the barycenter of the lattice with respect to the nominal center. **B**. Average time needed to reach the targets (*TT*). **C**. Average magnitude of the positional error (*PE*) at the end of the assistance phase. **D, E, F**: average amount of forces that act on the paretic arm during the treatment period: assistance (*AF*) during the assistive phase, restoring force (*RF*) needed to bring the paretic arm to match the target position and the holding force (*HF*) to maintain the desired position, respectively.

During the tested proprioceptive training session, the stroke subject was requested to match the position of the non paretic limb with her affected hand. The purpose of the training procedure was to induce the patient to use the proprioceptive information from the healthy limb for driving the movement of the paretic limb. The goal-oriented movement was assisted because the impairment level did not allow the subject to carry out the task by alone. A minimally assistive force (*AF*) that linked the end-effector to a moving target was turned on (assistance phase). If the target was not reached in the prescribed time (9.5s) a restoring force (*RF*) passively, but smoothly moved the hand to the target. The hand was stabilized there for 1s, by means of a holding force (*HF*). Recoil or jerky movements were carefully avoided.

Five targets-sets were used in this preliminary, single-session training experiment, with a randomization of the peripheral target selection. Figure 3.A, which shows the positional lattice achieved at the end of the assistance phase, suggests that in spite of the low level of the soft assistance the space representation tends to improve. Compare this graph with fig. 2.A: the space representation remains shrinked but the overall shift (Δx, Δy) is close to zero.

Graph 3.B shows the average amount of time required to reach the target (*TT*); we can see that it is smaller than the maximum time allowed by the training procedure (9.5s) but, at least for some targets, is close to the nominal time (1+3=4s) which would allow the hand of the patient to reach the final target in synchrony with the moving target, which is the origin of the assistive field. This is a useful check for the therapist who supervised the training protocol because it suggests that the parameters of assistance (*K,D,e*) were chosen in such a way to have a good trade-off, for the given patient, between assistance and performance, in order to maximize the active component of movement execution.

Graph 3.C represents the average magnitude of the positional error (*PE*) at the end of the assistance phase. This graph can be compared with the analogous graph 2.B, but it is important to take into account that they have a rather different meaning: in fig. 2.B *PE* is the error which expresses the deficit of position sense in the paretic arm, whereas in fig. 3.C *PE* is a combination of two deficits: 1) the purely motor deficit of the paretic arm (muscle weakness, defective recruitment of motor units, etc.) and 2) the relative proprioceptive deficits of the two arms, i.e. the degree of uncertainty about the localization of the paretic hand with respect to the healthy hand.

The last three panels (Fig 3.D, 3.E and 3.F) refer to the average magnitude of forces that were involved in the training phase. The assistive forces (*AF*) at the end of the assisted movement were high for distal targets where also the matching error was higher (fig 3.C). After a waiting interval of 8s, if the target position was not reached, a restoring force was activated (*RF*, fig 3.E) that brought the subject arm on the desired position. Then a holding force (*HF*, fig 3.F) maintained the paretic arm on the matching position for 1sec.

Table II stores the average values of the training indicators defined above at the end of the test session.

TABLE II. INDICATORS OF PROPRIOCEPTIVE TRAINING

	Parameters	***Patient***
1	Time to Target, *TT* [s]	7.19±0.14
2	Matching positional error, *PE* [cm]	3.78±0.22
3	Magnitude of the assistive force, *AF* [N]	2.98±0.18
4	Magnitude of the restoring force, *RF*[N]	4.47±0.16
5	Magnitude of the holding force, *HF*[N]	6.08±0.23

IV. DISCUSSION

In this study, we propose a new technique that allows to monitor the hand position sense of stroke patients and to organize training sessions with a double purpose: 1) improving the hand position sense and 2) improving motor performance.

The bimanual nature of the proposed robot system requires an attentional load that is not present in most systems of robot therapy in current use, in particular those that rely on passive mobilization or triggered assistance. Therefore, the first result of this preliminary feasibility study is that even for a rather severely impaired patient the system is accepted, the task is well understood, and the fatigue associated with the attentional load is not excessive. This was the primary goal in order to have sufficient ground for suggesting or organizing controlled clinical trials. What is still needed is to collect a larger body of information from healthy controls in order to have a reliable level of normality.

More in general there are open questions about the role of the hand position sense that need to be addressed in order to design optimal robot training: how important is monitoring the hand position sense before and during treatment? Which levels of accuracy of the hand position sense should be reached in order to achieve given levels of motor function?

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